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Analysis of Random Disturbances on Shop Floor in Modern Steel Production Dynamic Environment

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Abstract

In steel production practice, frequent deviations from a predictive schedule occur when the shop floor experiences various unexpected disturbances and render the schedules inefficient. In this paper, the typical disturbances and their effects on shop floor are studied comprehensively. The general repair procedures are put forward and can be simplified into four generic repair steps which can be used solely or in combination to repair a disruption. These disturbances can be treated as machine failure by virtue of the basic repair steps. Then a repair strategy based on conflict identification and elimination for machine failure is analyzed in detail. At last, a theorem is put forward for proving that a feasible rescheduling scheme can be found by the repair strategy for machine failure.

Keywords: steelmaking and continuous casting; hot rolling; dynamic environment; disturbances

1. Introduction

In modern steel production factory, pig iron is transformed into raw steel liquid by convert furnace (CF) and refining furnace (RF) in steelmaking and refining stages in order to produce molten steel of the correct grade or chemistry. The job unit in steelmaking and refining stages is Heat which is one ladle steel liquid process by one furnace. Molten steel is then cast into slabs on continuous caster (CC) in casting stage and the job unit in this stage is Cast. Slab is rolled into steel coils on Hot Strip Mill (HSM). The steelmaking-continuous casting process and hot rolling process are directly connected at high temperature and form an integrated and synchronized production environment [1]. The integrated scheduling of steel

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production not only needs to coordinate the production rhythm of steelmaking, refining and continuous-casting, but also needs to match up the material requirement of hot rolling production. However, in practical steel production process, a frequent deviation from a predictive schedule takes place when the shop experiences unexpected disturbances and renders the schedules infeasible. Therefore, it is a meaningful thing to analyze in detail and research real-time disturbances and their effects on shop floor.

Literatures [2~6] addressed only single disturbance on the shop, such as process time variation, rush orders, temperature compensation of molten steel, delay of molten steel in transport and unavailable slabs, and put forward a range of schedule repair and complete rescheduling strategies. Ref. [7~8] investigated two types of unexpected disturbance, such as delayed processing time and cancellation of order, arrival of urgent order and machine failure, and designed the corresponding heuristic algorithms for these disturbances. Some researchers analyzed three types of disturbance (machine breakdown, insufficient transportation ability and instability of production equipments; or cancellation of order, arrival of urgent order and machine failure; or the delayed delivery of slabs, machine breakdown, and failure to meet quality control standards) and presented several rescheduling methods for these disturbances [9~11]. The above researchers only analyzed single disturbance, two types of disturbance or three types of disturbance on the shop floor and didn't consider various disturbances all-around. This paper investigates comprehensively various disturbances on the shop floor in steel production dynamic environment and their effects as well as general repair procedure and basic repair steps, which can provide an effective decision support for theory and practice of the integrated steel production rescheduling.

The rest of this paper is organized as follows. Section 2 describes the typical unexpected disturbances and their effects on shop floor. The general repair procedure and basic repair step for these disturbances are introduced in Section 3. Section 4 describes a repair strategy for machine failure and a theorem. Finally, the research presented in this paper is summarized in Section 5.

2. Real-time disturbance events on shop floor

Steel production is a multi-constraint, multi stage and multi-objective complex process. According to previous researches and the practice of steel production, we divided random disturbances into two categories in this paper: internal and external disturbances. Internal disturbances mean that any great changes on its upstream (steelmaking /continuous casting stage) may result in great disturbance on its downstream (continuous casting/hot rolling stage). External disturbances refer to any great changes from outside of the workshop may result in great disturbance on production process inside the workshop. These typical disturbances and their effects on shop floor in steel production are shown in table 1.

Table 1. Disturbance events and their effects on shop floor

Categories	Disturbance events	Effects
• **External disturbances**	• Arrival of a new unexpected order	• The finished Heats are not affected. The unfinished Heats are affected and need to be rescheduled.
	• Urgent order, Change of priority of the Heats	• The end time has to change due to due date revision.
	• Cancellation of order	• Some Heats are not required to be produced.
	• Unavailability of slabs	• The coils of the non-available slabs are required to be redone.
• **Internal disturbances**	• Machine breakdown in the CF/RF/ HSM	• Machine unavailable for a period. Delay of the end time.
	• Delay of molten steel in transport	• Delay of the end time of steelmaking and refining.
	• Steel grade variation, temperature compensation of molten steel	• Change in end time of the refining stage.

Generally, at the steel-making stage, there will be the change of orders, machine failure and the smelting time which is beyond the prescribed limit, etc. At the continuous caster stage, there will be the random or dynamical arrival of Heats, steel grade variation (the chemical property of the molten steel have changed), steel leak in the continuous caster and machine failure, etc. At the hot rolling stage, there will be non-available slabs and HSM failure.

3. General repair procedure and basic repair step of the disturbances on shop floor

From the above analysis in section 2, the typical disturbances in shop floor may render the production process discontinuous and can even cause the production system paralysis. Therefore, it is necessary for us to find the general repair procedure for these disturbances to reduce the loss as much as possible. According to the characteristic of the steel production process, we presented general repair procedure and basic repair step of the typical disturbances as indicated by Table 2.

Table 2. General repair procedure and basic repair step of the disturbances on shop floor

Disturbance events	General repair procedure	Basic repair step
• Arrival of a new unexpected order	• Record the arrival time. Insert a time period equivalent to the process time of Heat on assigned machine and repair the schedule.	• Insert Heats iteratively
• Urgent order, Change of priority of Heats	• Record the new time for the Heat. Delete the non-urgent Heat from the existing position. Insert a time period equivalent to the process time of Heat and repair the schedule.	• Delete the Heat. Insert Heats iteratively
• Cancellation of order	• Identify the cancelled Heat. Remove it from the existing position.	• Delete the Heat.
• Unavailability of slabs	• Record the estimated time of availability. Delete the slab from current time. Insert a time period equal to the operation time of the slab on the machine.	• Delete the non-available slab. Insert a new slab.
• Machine breakdown in the CF/RF/ HSM	• Record the time of disturbance and introduce an idle time period equal to the breakdown time and repair the schedule. Or adjust the casting speed of the continuous casting machine.	• Insert an idle time
• Delay of molten steel in transport	• Identify the affected Heat. Record the increment in its end time. Insert a time period equal to the additional time.	• Insert an adjustment time
• Steel grade variation and temperature compensation of molten steel	• Identify the non-Heats. If the end time increases, insert a time period equal to the increment in process time and repair the schedule. In case, the process time is decreased, delete the heat and insert it again with same start time and new end time.	• Insert an adjustment time if time increased, or else deletion and insert Heat.

As can be seen from the Table 2, the general repair procedures can be simplified to basic repair steps further. These basic repair steps can be identified as: (1) Insert idle time; (2) Insert adjustment time; (3) Insert operation; (4) Delete operation. The four basic repair steps may be used exclusively or in combination to repair a disruption. If we look on 'insert idle time' as a virtual operation and 'insert adjustment time' as an independent virtual operation, all schedule repair steps are viewed as 'insert operation' and 'delete operation'. In particular, schedule repair for machine failures can be looked as the typical 'insert operation'; schedule repair for the arrival of new job, urgent job and process time variation can be viewed as 'delete/insert operation'. To a certain extent, the repair for most disturbances can be looked as a schedule repair for machine failure by the four basic repair steps. The above is a general representation of the diverse disturbances on shop floor, and is by no means exhaustive.

4. A repair strategy for machine failure in steel production dynamic environment

The machine failure is the common disturbance in steel dynamic production. The flowchart in Fig.1 illustrates the repair strategy for machine failure. Let M_{break} denotes the breakdown machine, t_b and t_e denote the start and end point of the down time, $o_{i^d j^d}$ denotes the ith Heat in jth stage is interrupted. When the machine broke down, we first seek whether similar parallel machines is idle or not. If there is an idle parallel machine, the interrupted Heat $o_{i^d j^d}$ and the unfinished Heats in M_{break} are rearranged to the idle machine. If not, the heuristic rule $Conflict\_I$ and $Conflict\_E$ are applied to identify and eliminate conflicts. If all the Heats are finished, a new schedule is output and stop. Where $Conflict\_I$ and $Conflict\_E$ heuristic rule are shown in Fig.2.

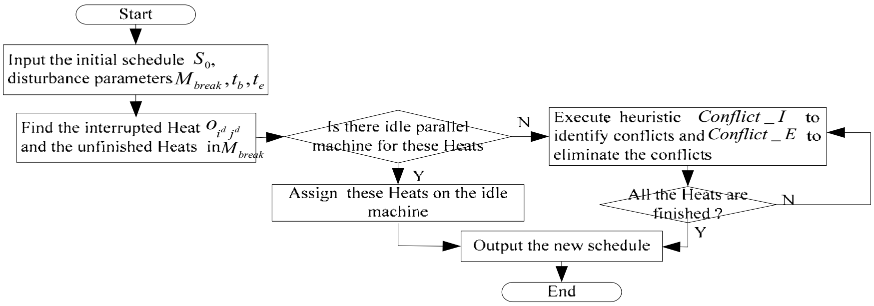

Fig.1 The repair strategy for the machine breakdown

```
1  Function Conflict_I(o_pj : Heat, Set(o_pj) : HeatList)
2    Δf(o_pj) := 0; CS(o_pj) := ∅;
3    Sort the Heats in Set(o_pj) by starting time in an ascendant order;
4    for(r := 1; r++, r ≤ |Set(o_pj)|) do
5      if(s_qj ≤ s_pj < c_qj) then
         // s_qj is the start time of o_qj, s_pj is the start time of o_pj,
         // c_qj is the end time of o_qj
6        Δf(o_pj) := c_qj − s_pj;
7      end if
8      if(s_pj ≤ s_qj < c_pj) then  // c_pj is the end time of o_pj
9        CS(o_pj) = {o_qj};
10       go to line 13;
11     end if
12   end for;
13   return ObjConflict; //ObjConflict : Δf(o_pj), CS(o_pj);
14 end
```

(a)

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Function Conflict_E(o_pj : Heat)
  For Δf(o_pj) and CS(o_pj) obtained from the Conflict_I;
  if(CS(o_pj) = ∅ ∧ Δf(o_pj) = 0) then
    reserve the previous starting time of o_pj;
  end if
  if(CS(o_pj) = ∅ ∧ Δf(o_pj) > 0) then
    s_pj := s_pj + Δf(o_pj);
    update starting time of the other unfinished Heats
    which have temporal constraints with o_pj;
  end if
  if(CS(o_pj) ≠ ∅ ∧ Δf(o_pj) = 0) then
    reserve the previous starting time of o_pj;
    update starting time of the other unfinished Heats in CS(o_pj);
  end if
  if(CS(o_pj) ≠ ∅ ∧ Δf(o_pj) > 0) then
    s_pj := s_pj + Δf(o_pj);
    update starting time of the other unfinished Heats
    which have temporal constraints with o_pj;
    update starting time of the other unfinished Heats in CS(o_pj);
  end if
end
```

(b)

Fig. 2 (a) the $Conflict\_I$ heuristic rule; (b) the $Conflict\_E$ heuristic rule

In order to verify the feasibility of the repair strategy under machine breakdown, we present a theorem to prove that a feasible rescheduling scheme can be obtained on condition that $t_b \le dd_i - \sum_{k=j^d}^{s} p_{i^d k}$. Otherwise, the repair strategy will be invalid and a complete rescheduling needs to be done.

Theorem If the machine M_{break} breaks down during the time interval $[t_b, t_e]$ and the processing Heat $o_{i^d j^d}$ is interrupted, the necessary condition for a feasible rescheduling scheme is $t_b \le dd_i - \sum_{k=j^d}^{s} p_{i^d k}$. (Where $p_{i^d k}$ denotes the processed time of the Heat i^d at the k stage, dd_i denotes the due date of the Heat i .)

Proof. Suppose there exits a feasible rescheduling scheme π', the Heats o_{qs} and $o_{i^d s}$ are assigned to the same machine and o_{qs} is prior to $o_{i^d s}$. Therefore, $c'_{i^d s} \le dd_i$ ($c'_{i^d s}$ denotes the end time of the interrupted heats i^d at the s stage). Generally, $s'_{i^d j^d} \geq t_b$ ($s'_{i^d j^d}$ denotes the start time of the interrupted Heats i^d at the j^d stage) and $c'_{i^d s} = s'_{i^d s} + p_{i^d s}$, so $s'_{i^d s} = \max\{c'_{qs}, c'_{i^d s-1}\} \geq c'_{i^d s-1}$, and then $c'_{i^d s-1} + p_{i^d s}$ = $s'_{i^d s-1} + p_{i^d s-1} + p_{i^d s}$ = $s'_{i^d s-1} + \sum_{k=s-1}^{s} p_{i^d k}$ = $\cdots$ $= s'_{i^d j^d} + \sum_{k=j^d}^{s} p_{i^d k}$. And $c'_{i^d s} \geq c'_{i^d s-1} + p_{i^d s}$, so $c'_{i^d s} \geq s'_{i^d j^d} + \sum_{k=j^d}^{s} p_{i^d k}$ and $dd_i \geq t_b + \sum_{k=j^d}^{s} p_{i^d k}$. Hence, we have $t_b \leq dd_i - \sum_{k=j^d}^{s} p_{i^d k}$. □

5. Conclusions

The real-time disturbances and their effects on shop floor in steelworks have been analyzed comprehensively in this paper. The general repair procedures and basic repair steps have been put forward. We looked the repair of most disturbances as a repair for machine failure by means of these repair steps. Aiming the repair for machine failure, we put forward a theorem to prove its feasibility under certain conditions.

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